

Status of Constraints on Supersymmetry

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A short summary of constraints on the parameter space of supersymmetric models is given. Experimental limits from high energy colliders, electroweak precision data, flavor and Higgs physics, and cosmology are considered. The main focus is on the MSSM with conserved R- and CP-parity and minimal flavor violation, but more general scenarios and extended models will also be discussed briefly.

1. INTRODUCTION

The purpose of this contribution is to summarize the constraints on supersymmetric models from various experimental results. Due to the large wealth of experimental searches for physics beyond the standard model (SM) and phenomenological studies on supersymmetry (SUSY) it is impossible to cover all of them in this short review. Thus the author apologizes that many valuable studies are not mentioned or cited in this report.

To set the scene, a short review of the most widely studied SUSY models is given in the next section. The following sections discuss constraints on the parameter space of these models from high energy colliders, electroweak precision data, flavor and Higgs physics, and cosmology, respectively. Finally, some qualitative comments on more general SUSY models are presented before the summary.

2. SUSY MODELS

The most extensively studied SUSY model is the Minimal Supersymmetric Standard Model (MSSM), with the particle content listed in Table I. In addition the MSSM imposes R-parity, assigning $R_p = +1$ for the Higgs boson, gauge bosons, leptons, and quarks, and $R_p = -1$ for their supersymmetric partners (neutralinos, charginos, gluino, sleptons, and squarks). As a result the superpotential has the form

$$W_{\text{MSSM}} = y_u \hat{Q} \cdot \hat{H}_2 \hat{U}^c + y_d \hat{Q} \cdot \hat{H}_1 \hat{D}^c + y_e \hat{L} \cdot \hat{H}_1 \hat{E}^c - \mu \hat{H}_1 \cdot \hat{H}_2. \quad (1)$$

For a general introduction to the MSSM and notational definitions, see *e. g.* Ref. [1].

In the major part of this work, an even more minimal version of the MSSM is assumed where the CKM matrix is the only source of CP violation and flavor violation. In other words, the SUSY breaking parameters are assumed to be real and flavor blind.

This still leaves more than one dozen *a priori* unknown SUSY breaking parameters. Many experimental searches and phenomenological analyses thus consider specific SUSY breaking scenarios:

- *mSUGRA/CMSSM*: In *minimal Supergravity* (mSUGRA) or the *constrained MSSM* (CMSSM) the scale of SUSY breaking is situated near the scale of gauge coupling unification, $M_{\text{GUT}} \approx 2 \times 10^{16}$ GeV. At this scale, there is one common mass parameter each for the gauginos, scalars and triple-scalar couplings (A-terms), respectively. At lower energies, a more complex SUSY mass spectrum emerges due to renormalization group running. As a result, the colored SUSY partners (squarks and gluino) are substantially heavier than the weakly coupled SUSY particles. The lightest SUSY particle (LSP) is typically the lightest neutralino $\tilde{\chi}_1^0$, with $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(100 \text{ GeV})$.

Table I: Particle content of the MSSM

Spin 0	Spin 1/2	Spin 1
Neutral Higgses h_0, H_0, A_0	Neutralinos $\tilde{\chi}_1^0 \dots \tilde{\chi}_4^0$	Photon γ Z boson
Charged Higgs H^\pm	Chargino $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	W^\pm bosons
	Gluino \tilde{g}	gluon g
sleptons $\tilde{e}, \tilde{\mu}, \tilde{\nu}, \dots$ squarks $\tilde{u}, \tilde{d}, \dots$	leptons e, μ, ν, \dots quarks u, d, \dots	

- *GMSB*: In *gauge mediated SUSY breaking* (GMSB) the breaking of supersymmetry is transmitted by gauge interactions. The minimal version, which introduces messengers in the fundamental representation of SU(5), produces $\mathcal{O}(100 \text{ GeV})$ SUSY masses for a messenger scale $\Lambda_{\text{mess}} \sim 100 \text{ TeV}$. Similar to mSUGRA, the gauge couplings and gaugino masses unify at M_{GUT} , but the sfermion masses do not unify at any scale. The triple-scalar couplings (A -terms) are almost zero at the messenger scale $\Lambda_{\text{mess}} \sim 100 \text{ TeV}$ and remain relatively small at the electroweak scale. In GSMB, the LSP is typically the gravitino, with $m_{\tilde{G}} \sim 100 \text{ eV} \dots 1 \text{ GeV}$.
- *AMSB*: In general, soft supersymmetry breaking terms receive contributions from the super-Weyl anomaly via loop effects. *Anomaly mediated supersymmetry breaking* (AMSB) becomes relevant only if other SUSY breaking mechanisms are suppressed or absent. AMSB predicts the gaugino mass ratios $|M_1| : |M_2| : |M_3| \approx 2.8 : 1 : 7.1$, so that the LSP is typically the lightest neutralino $\tilde{\chi}_1^0$ with a dominant wino component. The chargino $\tilde{\chi}_1^\pm$ is a almost pure wino and very close in mass to the LSP.

A shortcoming of the MSSM is the appearance of the μ -term (the last term in eq. (1)) which must be of the order of the electroweak scale for successful electroweak symmetry breaking, leading to the unnatural hierarchy $\mu \ll M_{\text{GUT}}$. One solution to this puzzle is the introduction of an additional singlet chiral superfield so that the general superpotential becomes

$$W_{\text{MSSM+S}} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \kappa \hat{S}^3 + m_S \hat{S}^2 + t_S \hat{S} + \text{Yukawa terms.} \quad (2)$$

In this general form the superpotential again has several dimensionful parameters which have to be much smaller than the GUT scale. However, the unwanted terms can be set to zero by introducing new symmetries, for example

- *Next-to-minimal MSSM (NMSSM)*: A global \mathbb{Z}_3 symmetry mandates $m_S = t_S = 0$, but could lead to cosmological domain walls [2].
- *Nearly minimal MSSM (nMSSM)*: Imposing a global \mathbb{Z}_5 or \mathbb{Z}_7 symmetry forbids all singlet self-couplings at tree-level, $m_S = t_S = \kappa = 0$. However, supergravity effects combined with SUSY breaking allow a contribution to t_S at the six- or seven-loop level, naturally generating a value $t_S \sim \mathcal{O}(\text{TeV})$ as required for successful electroweak symmetry breaking [3].
- *U(1)-extended MSSM (UMSSM)*: This model introduces a U(1) gauge symmetry under which the Higgs and singlet field are charged. As a result, $m_S = t_S = \kappa = 0$, but new D-term contributions to the Higgs potential appear which play an important role in achieving realistic electroweak symmetry breaking [4].

3. HIGH ENERGY COLLIDERS

Searches for SUSY particles at e^+e^- colliders are largely independent on the details of the model or scenario. Roughly speaking, results from LEP exclude sparticles up to the beam energy $E_{\text{beam}} \sim 100 \text{ GeV}$. The actual exclusion bounds [5, 6] are listed in Table II. The exact limits vary as a result of the different pair-production

Table II: Lower limits on SUSY particle masses from LEP searches

Sparticle	lower limit [GeV]	Sparticle	lower limit [GeV]
$\tilde{\chi}_2^0$	62.4	$\tilde{\nu}$	94.0
$\tilde{\chi}_3^0$	99.9	\tilde{e}_L	107.0
$\tilde{\chi}_4^0$	116.0	$\tilde{\mu}_R$	91.0
$\tilde{\chi}_1^\pm$	94.0	$\tilde{\tau}_1$	81.9
$\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$	97.0	\tilde{t}_1	92.6

Table III: Lower limits on SUSY particle masses from Tevatron searches

Sparticle	mSUGRA/CMSSM limit [GeV]	more general MSSM limit [GeV]
\tilde{g}	308	~ 150
\tilde{q}	380	LEP limit
$\tilde{\chi}_1^\pm$	140	LEP limit

cross sections for different particles types. Furthermore, some of the searches fail if the mass difference between the pair-produced sparticle \tilde{X} and the LSP becomes too small, $m_{\tilde{X}} - m_{\text{LSP}} \lesssim \text{few GeV}$, see Refs. [5, 6] for details.

SUSY searches at hadron colliders are more intricate due to the large backgrounds. In most cases, a large signal-to-background ratio is only achievable by designing the selection strategy for some set of SUSY scenarios. For SUSY searches at the Tevatron, mSUGRA/CMSSM scenarios are usually taken as benchmark [7]. However, when these results are expressed for more general MSSM scenarios the limits become much weaker and might drop below the LEP limits [7, 8], see Table III. More details about Tevatron searches and prospects for SUSY discovery at the LHC are given in the contributions by T. Adams [9] and O. Brandt [10] at this conference.

The MSSM parameter space is also constrained indirectly by the lower limit on the mass of a SM-like Higgs boson from LEP searches, $m_h^{\text{SM}} > 114.4 \text{ GeV}$ [11]. In the MSSM the lightest CP-even Higgs boson mass can be calculated as a function of other parameters. The leading tree-level and one-loop contributions are given by

$$m_h \lesssim M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \left[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \right] + \dots, \quad X_t = A_t - \frac{\mu}{\tan \beta}, \quad (3)$$

where the dots stand for higher-order corrections. To be compatible with the LEP limit, the terms in eq. (3) need to be large so that at least one of the following conditions must be met:

- $\tan \beta \gg 1$ to maximize the tree-level term $M_Z^2 \cos^2 2\beta$,
- Large average stop mass, $m_{\tilde{t}}^2 = m_{\tilde{t}_1} m_{\tilde{t}_2} \gtrsim (1 \text{ TeV})^2$,
- Large stop mixing to enhance the $X_t^2/m_{\tilde{t}}^2$ term.

In extended models with extra singlets (NMSSM, nMSSM) or gauge groups (UMSSM) the constraints on the SUSY parameter space from the m_h limit are much less severe due to new positive tree-level contributions to m_h [12].

4. ELECTROWEAK PRECISION DATA

Loop corrections from SUSY particles affect the predictions for electroweak precision observables. Much effort has been invested in calculating the radiative corrections from SUSY loops. The current state of the art in the MSSM encompasses complete one-loop corrections [13] and leading two-loop corrections of order $\mathcal{O}(\alpha\alpha_s)$ [14] and $\mathcal{O}(\alpha y_{t,b}^2)$ [15]. For the NMSSM and other extensions only partial one-loop results are known.

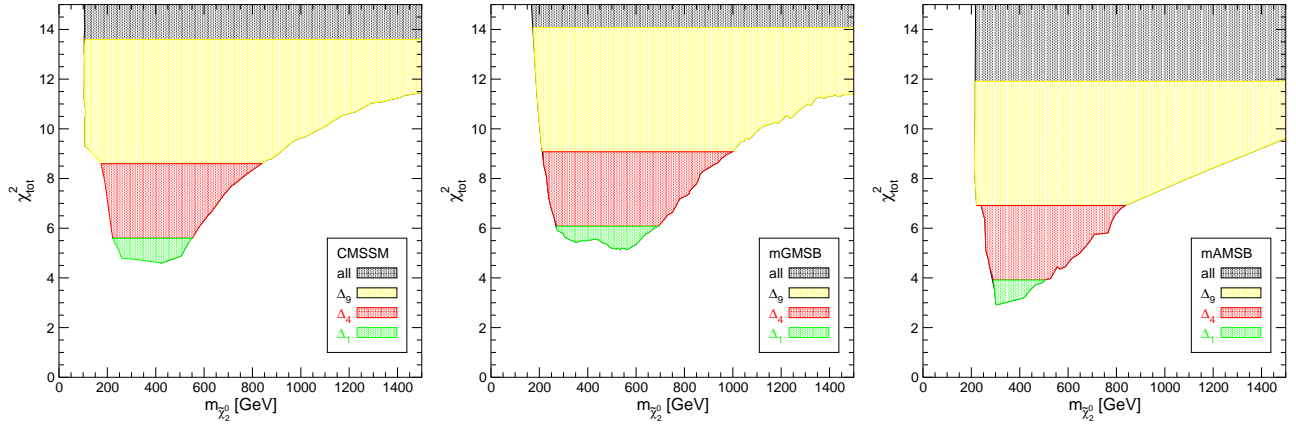


Figure 1: χ^2 fit to electroweak precision observables as a function of the mass of the second neutralino $\tilde{\chi}_2^0$ for the mSUGRA/CMSSM, GMSB, and AMSB scenarios; from Ref. [17].

The most important quantities that have been measured with high precision and that receive sizable corrections from new physics are:

- The W -boson mass M_W , which is determined from the muon decay width by including the relevant radiative corrections for the process $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$.
- The effective weak mixing angle of the Z boson, defined through the effective vector and axial vector couplings of the Z boson on the Z resonance, $\sin \theta_{\text{eff}} = \frac{1}{4} \left(1 - \text{Re} \frac{v_{\text{eff}}}{a_{\text{eff}}} \right)$. The effective mixing angle can be defined for all fermion flavors although the numerical differences are small except for the $Z b \bar{b}$ vertex.
- The total Z -boson width, Γ_Z , and the total Z peak cross section $\sigma[e^+e^- \rightarrow Z \rightarrow f \bar{f}]$. Both of these quantities are closely related to the coupling combination $v_{\text{eff}}^2 + a_{\text{eff}}^2$.
- The muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$.

By performing a fit of the MSSM predictions for these quantities to the experimentally determined values [16, 17] one finds in general good agreement for light sleptons and gauginos. The reason for this is two-fold: *(i)* in the SM the best fit to the electroweak precision observables corresponds to a Higgs mass of $m_h \approx 87$ GeV, which creates a tension with the lower limit from direct searches, $m_h > 114.4$ GeV. The new contributions from slepton-gaugino loops can push the best-fit Higgs mass to values $m_h > 100$ GeV, thus improving the overall goodness-of-fit. *(ii)* SUSY loop contributions from sleptons and gauginos can account for the 3.3σ discrepancy between the SM prediction and the measured value of the muon anomalous magnetic moment, $a_\mu^{\text{exp}} - a_\mu^{\text{theo}} = (27.5 \pm 8.4) \times 10^{-10}$ [18].

The results of a χ^2 fit for the mSUGRA/CMSSM, GMSB, and AMSB scenarios are shown in Fig. 1. The plots show the best fit χ^2 as a function of the mass of the neutralino $\tilde{\chi}_2^0$, which has a dominant wino or higgsino component in these scenarios. As evident from the figure, in all three scenarios a light neutralino with $m_{\tilde{\chi}_2^0} \sim 200 \dots 700$ GeV is preferred, while neutralino masses above 1 TeV are strongly disfavored.

5. FLAVOR AND HIGGS PHYSICS

Rare decays of heavy flavor mesons are very sensitive to new physics effects. For SUSY models these effects are enhanced for large values of $\tan \beta$ since the Yukawa couplings of the down-type fermions become large, $y_d =$

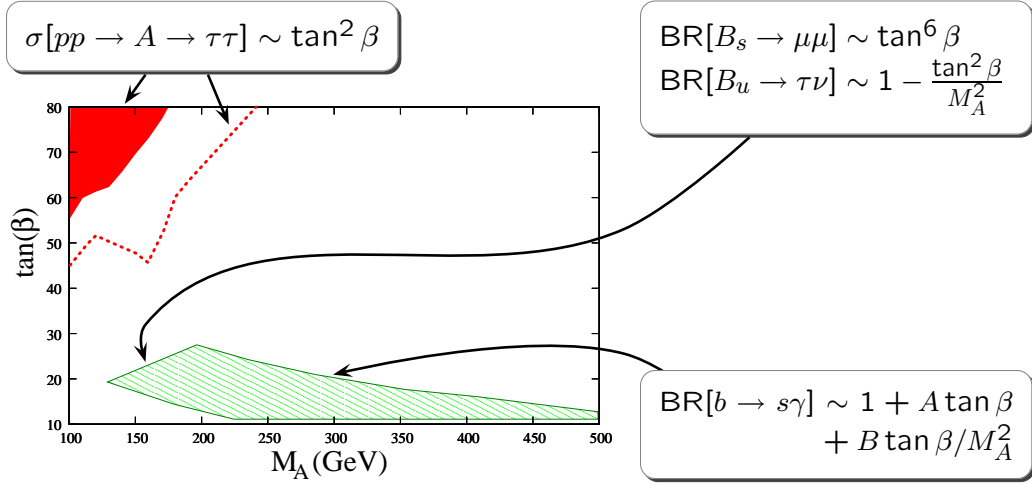


Figure 2: Constraints on the M_A - $\tan\beta$ parameter plane from B and Higgs physics in the MSSM; from Ref. [19]. The other SUSY parameters are chosen to be $\mu = -100$ GeV, $X_t = 2.4$ TeV, $m_{\tilde{q}} = 1$ TeV, $m_{\tilde{g}} = 800$ GeV. The red region is excluded by non-observation of A_0 production at the Tevatron (solid filled: CDF [20]; dotted: DØ [21]), while only the green region is allowed by rare B -decay measurements.

$m_d/v \times \tan\beta$. Schematically, the dependence of rare B decays on $\tan\beta$ in the MSSM reads

$$\text{BR}[B_s \rightarrow \mu\mu] \sim \frac{\tan^6 \beta}{M_A^4}, \quad (4)$$

$$\text{BR}[B_u \rightarrow \tau\nu] \sim \left[1 - \frac{m_B^2}{M_A^2} \tan^2 \beta \right]^2, \quad (5)$$

$$\text{BR}[b \rightarrow s\gamma] \sim 1 + A \tan\beta + B \tan\beta / M_A^2, \quad (6)$$

where A and B are coefficient that depend on other SUSY parameters in a non-trivial way.

In the region of large $\tan\beta$, the production cross section for the CP-odd Higgs boson A_0 at hadron colliders is also increased,

$$\sigma[pp \rightarrow A \rightarrow \tau\tau] \sim \tan^2 \beta, \quad (7)$$

establishing an intricate relationship between heavy-flavor and Higgs observables with respect to the SUSY parameter space [19].

The negative searches of the A_0 boson at the Tevatron [20, 21] exclude the parameter region of large $\tan\beta$ and small M_A , with very little dependence on other SUSY parameters. Similarly, the current experimental upper limit on $\text{BR}[B_s \rightarrow \mu\mu]$ is most important for large $\tan\beta$ and small M_A , although with some dependence on other variables, $m_{\tilde{t}_{1,2}}, m_{\tilde{b}_{1,2}}, \mu$. Depending on the value of these quantities the constraint from $\text{BR}[B_s \rightarrow \mu\mu]$ on the SUSY parameter space can be stronger or weaker than the bound from A_0 searches. The measurement of $\text{BR}[B_u \rightarrow \tau\nu]$, in good agreement with the SM, allows either the region of small $\tan\beta/M_A$ or of large $\tan\beta/M_A$ (although the latter is severely limited by the previous two observables), while intermediate values of $\tan\beta/M_A \sim 1/4 \text{ GeV}^{-1}$ are disfavored. Finally, $\text{BR}[b \rightarrow s\gamma]$ varies relatively mildly as a function of M_A , but it places both an lower and upper bound on $\tan\beta$. However, the prediction of $\text{BR}[b \rightarrow s\gamma]$ is affected by many SUSY parameters so that quantitative conclusions depend quite strongly on the scenario.

The flavor physics and Higgs constraints mentioned above are summarized in Fig. 2 for the MSSM. Note that while the B -physics observables seem to impose very severe limits on M_A and $\tan\beta$ these bounds depend substantially on other SUSY parameters μ , $m_{\tilde{g}}$, X_t , and $m_{\tilde{q}}$, which for the purpose of this analysis is assumed to be a common mass for all squarks. The most robust, scenario-independent constraint comes from A_0 searches which can be expressed roughly as $M_A / \tan\beta \gtrsim 3 \text{ GeV}$.

6. COSMOLOGY

The derivation of bounds on the SUSY parameter space from cosmology depends on many details of the SUSY model as well as the history of the universe and might be impacted by theoretical uncertainties that have not been quantified so far. Nevertheless it is illustrative to study some of the constraints since even at a qualitative level they affect the parameter structure of the model.

6.1. Dark Matter

For conserved R-parity, the LSP is a stable particle and could provide a good cold dark matter candidate as long as it is neutral and weakly interacting. Within the standard cosmological model it is possible to calculate the expected relic dark matter density for a given SUSY model, although often the results depend on many model parameters. However typically only certain corners of the parameter space give good agreement with the measured value from the cosmic microwave background, $\Omega_{\text{DM}} h^2 = 0.110 \pm 0.006$ [22]. There are three main possibilities for LSPs as viable dark matter candidates in the MSSM:

- *Lightest neutralino* $\tilde{\chi}_1^0$: If the lightest neutralino has a dominant bino component, annihilation into gauge bosons is strongly suppressed. Thus, to be compatible with the observed dark matter density, one of the following enhancement mechanisms for the annihilation cross section needs to be present:
 - Light sleptons, $m_{\tilde{l}} \approx 100$ GeV, together with $m_{\tilde{\chi}_1^0} < 100$ GeV lead to a sufficiently large t-channel contribution. This parameter region is often called the “*bulk*” region.
 - Co-annihilation: if the mass difference to the next-to-lightest SUSY particle (NSLP) \tilde{X} is small, $m_{\tilde{X}} - m_{\tilde{\chi}_1^0} \ll m_{\tilde{\chi}_1^0}$, both particles annihilate in parallel in the early universe. A large $\tilde{X}\tilde{\chi}_1^0$ co-annihilation cross section can then compensate for a small $\tilde{\chi}_1^0\tilde{\chi}_1^0$ annihilation rate.
 - Resonant annihilation: if the mass of the neutralino is close to half of the mass of a possible bosonic s-channel resonance, $2m_{\tilde{\chi}_1^0} \approx M_Z, m_h, M_A$, neutralino pair annihilation can proceed efficiently through this resonance.

Alternatively, the neutralino $\tilde{\chi}_1^0$ could be an admixture with sizable wino and/or higgsino components. In this case, the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ annihilation rate into gauge boson naturally has the right order of magnitude for $m_{\tilde{\chi}_1^0} \sim \mathcal{O}(\text{few } 100 \text{ GeV})$.

- *Sneutrino* $\tilde{\nu}$: It has been known for many years that the L-sneutrino $\tilde{\nu}_L$ cannot be the dominant source of dark matter since it would lead to a collision rate with ordinary matter that is much larger than the current bounds from direct detection experiments. However, as indicated by the observation of neutrino oscillations, it is likely that also L- and R-sneutrinos mix with each other. A sneutrino with a dominant R-sneutrino ($\tilde{\nu}_R$) component would constitute a good dark matter candidate in agreement with all constraints for $10 \text{ GeV} \lesssim m_{\tilde{\nu}_R} \lesssim 1 \text{ TeV}$ [23].
- *Gravitino* \tilde{G} : Gravitino dark matter can be produced in two ways, see *e. g.* [24]:
 - Gravitinos can be produced non-thermally from decays of the NLSP \tilde{X} . Late decays of the NLSP can lead to entropy overproduction and thus hot dark matter in disagreement with large scale structure formation. Since

$$\Gamma[\tilde{X} \rightarrow X\tilde{G}] \propto \frac{m_{\tilde{X}}^5}{m_{\tilde{G}}^2} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{X}}^2}\right)^4 \quad (8)$$

this places a lower bound $m_{\tilde{X}} > 0.5 \text{ TeV}$. If this bound is satisfied the correct relic abundance can be obtained for gravitino masses in the range $1 \text{ GeV} \lesssim m_{\tilde{G}} \lesssim 700 \text{ GeV}$ [24].

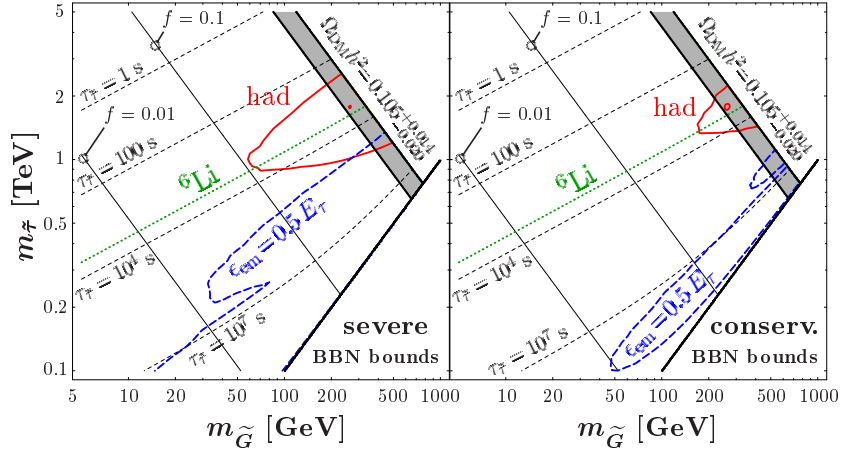


Figure 3: Constraints on the $\tilde{\tau}_1$ and \tilde{G} masses from BBN due to hadronic and electromagnetic energy release from late $\tilde{\tau}_1$ decays; from Ref. [25]. The dashed lines show contours of equal $\tilde{\tau}_1$ stau lifetime, while the gray band indicates the region compatible with the correct relic density. The difference between the left and right plot serve as an illustration of the uncertainty for primordial nuclei abundances.

- Alternatively, gravitinos can be produced thermally directly from the hot plasma in the early universe. When produced from thermal equilibrium the gravitino abundance is much too large (“gravitino problem”). Therefore the reheating temperature T_R of the universe is required to be much smaller than the gravitino equilibrium temperature. In this case non-equilibrium thermal production is viable for $1 \text{ keV} \lesssim m_{\tilde{G}} \lesssim 1 \text{ TeV}$, depending on the exact value of T_R .

6.2. Big-bang Nucleosynthesis

If the LSP is a gravitino the energy released from NLSP decays can be problematic for successful big-bang nucleosynthesis (BBN). Hadronic and electromagnetic showers emitted by the NLSP decays can dissociate light element nuclei and thus shift the predicted ratios of element abundances. For the NLSP to disrupt BBN, the NLSP lifetime has to be $\tau_{\text{NLSP}} \gtrsim 100 \text{ s}$. Therefore this constraint excludes small NLSP masses and large gravitino masses.

For $\tilde{\tau}_1$ as NLSP, the detailed constraints are shown in Fig. 3 [25]. Depending on assumptions in the evaluation of the primordial nuclei abundances the BBN constraints place an upper bound $m_{\tilde{G}} \lesssim 100\text{--}500 \text{ GeV}$.

6.3. Baryogenesis

New physics beyond the SM is needed to explain the excess of matter over antimatter in the universe. The two most well-known mechanisms are leptogenesis and electroweak baryogenesis. *Leptogenesis* generates the particle-antiparticle asymmetry through the decay of long-lived heavy neutrinos ν_R or sneutrinos $\tilde{\nu}_R$. This mechanism imposes strong constraints on the masses, mixings and CP phases of the right-chiral (s)neutrino sector, but if $m_{\nu_R} \gg 1 \text{ TeV}$ it is in general not testable by collider experiments. In *electroweak baryogenesis*, on the other hand, the matter asymmetry is created by the electroweak phase transition if it is strongly first order and involves CP-violating currents.

In the MSSM a strong first order phase transition is only realizable if one of the stops is light, $m_{\tilde{t}_1} < 140 \text{ GeV}$ [26]. The Higgs mass bound, $m_h > 114.4 \text{ GeV}$ then requires the other stop to be much heavier, $m_{\tilde{t}_2} > 3 \text{ TeV}$. In singlet extensions (NMSSM/nMSSM) the strength of the electroweak phase transition is increased by the new Higgs-singlet couplings and no special values for the stop masses are needed [27].

CP-violating currents can originate from the chargino/neutralino sector both in the MSSM and NMSSM/nMSSM. However, due to strong limits on electric dipole moments of the electron and neutrino, such CP phases are only

allowed for very large masses of the first generation sfermions, $m_{\tilde{e}}, m_{\tilde{q}} \gtrsim 10$ TeV. In the NMSSM/nMSSM the CP phase responsible for baryogenesis can also be implemented in the Higgs sector, leading to weaker constraints from electric dipole moments [28].

6.4. Ultra-light neutralinos

Neutralinos $\tilde{\chi}_1^0$ that are almost exclusively bino and have negligible wino and higgsino components are not constrained by collider data. The only relevant bounds come from astrophysics and cosmology [29]:

- For conserved R-parity a lower bound $m_{\tilde{\chi}_1^0} > 3$ GeV has to be imposed to avoid dark matter overproduction.
- Independent of R-parity conservation, very light neutralinos can contribute to supernova cooling for moderately light selectrons, $m_{\tilde{e}} \lesssim 500$ GeV. The observations from SN 1987A thus lead to a lower limit $m_{\tilde{\chi}_1^0} > 200$ MeV in this case. However, for $m_{\tilde{e}} > 1200$ GeV no constraint on the neutralino mass can be derived from supernova cooling.
- Very light neutralinos have a large free-streaming length and thus can jeopardize structure formation. This consideration excludes values of $m_{\tilde{\chi}_1^0}$ between 1 eV and 1 keV.

In summary, limits on light bino-like $\tilde{\chi}_1^0$ are very weak and $m_{\tilde{\chi}_1^0}$ is largely unconstrained.

7. EXTENDED MODELS

In this section the assumptions of R-parity conservation, minimal flavor violation and CP conservation will be relaxed one at the time. As a result, many bounds on the MSSM parameter space become weaker or disappear altogether.

7.1. Flavor violation

The sfermion soft breaking parameters can introduce new sources of flavor violation, in particular leading to potentially large flavor changing neutral currents (FCNCs). FCNCs are strongly constrained by K^0 , D^0 and B^0 mixing, rare B decays, and limits on lepton flavor violating processes such as $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conversion, *etc.* However, if new flavor violating terms are introduced in the 2nd and 3rd generation only, flavor mixing sfermion mass terms as large as $\mathcal{O}(M_{\text{SUSY}})$ are still allowed by present data [30].

7.2. CP violation

Complex CP phases in the gaugino sector and in the parameters of the 1st generation sfermions are strongly constrained by electric dipole moments (see previous section). Sizable CP violation is however allowed in the Higgs sector and the sector of the 3rd generation sfermions.

7.3. R-parity violation

Without R-parity conservation the MSSM superpotential is extended by the following couplings:

$$W_{\tilde{\mathcal{R}}_p \text{MSSM}} = W_{\text{MSSM}} + \frac{1}{2} \lambda_{ijk} L_i \cdot L_j E_k^c + \frac{1}{2} \lambda'_{ijk} L_i \cdot Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c \cdot D_j^c D_k^c. \quad (9)$$

The product of baryon-number violating and lepton-number violating couplings is strongly constrained by proton decay, *i. e.* $|\lambda''_{ijk} \lambda_{ijk}|, |\lambda'_{ijk} \lambda'_{ijk}| \ll 1$. Such a structure could be explained by discrete symmetries while still allowing

Table IV: Simplified summary of parameter constraints in the MSSM without and with R-parity violation and in the NMSSM.

MSSM + R_p	MSSM + \not{R}_p	NMSSM & other ext.
$m_{\tilde{l}}, m_{\tilde{q}}, m_{\tilde{\chi}_{1\pm}} \gtrsim 100 \text{ GeV}, m_{H^\pm} \gtrsim 100 \text{ GeV}$		
$m_{\tilde{g}} \gtrsim 150 \text{ GeV}$	$m_{\tilde{g}} \gtrsim 51 \text{ GeV}$	$m_{\tilde{g}} \gtrsim 150 \text{ GeV}$
$m_{\tilde{\tau}_1} \gtrsim 82 \text{ GeV}$	$m_{\tilde{\tau}_1} \gtrsim 11 \text{ GeV}$	$m_{\tilde{\tau}_1} \gtrsim 82 \text{ GeV}$
$m_{\tilde{\mu}}, m_{\tilde{\chi}_2^0} < 1 \text{ TeV}$		
$m_{\tilde{\chi}_1^0} > 3 \text{ GeV}$	—	?
$\tan \beta \gtrsim 3$	—	—
$\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 1 \text{ TeV}$ and/or large A_t	?	
$M_A / \tan \beta \gtrsim 3 \text{ GeV}$		—

some non-zero R-parity violating couplings. In the absence of B -violating terms the L -violating interactions are mainly constrained by data on neutrino masses, leading to $|\lambda_{ijk}|, |\lambda'_{ijk}| \lesssim 10^{-5} \dots 0.6$ [31].

If R-parity is violated the LSP is not stable and the signatures for SUSY particles production at colliders are dramatically altered. As a result, experimental bounds for several SUSY particles becomes much weaker. In particular one finds $m_{\tilde{g}} > 51 \text{ GeV}$ [32], $m_{\tilde{b}_1} > 7.5 \text{ GeV}$, $m_{\tilde{\tau}_1} > 11 \text{ GeV}$ [33], and $m_h > 82 \text{ GeV}$ [34].

8. SUMMARY

Due to the complexity of the SUSY parameters space (even in the MSSM with R-parity conservation, minimal flavor violation and CP conservation) and the large number of experimental results it is difficult to summarize all constraints in a simple picture. In Table IV a rough overview of the main limits from direct sparticle and Higgs searches, as well as electroweak precision data and flavor physics is attempted. The three columns in the table correspond to the MSSM with and without R-parity conservation and the NMSSM, respectively. The NMSSM limits also apply for the nMSSM and UMSSM. A “—” indicates that no bound exists while “?” stands for cases where the final quantitative conclusion is not known yet. The limits in the first three lines stem for direct searches at high-energy colliders, while the upper bound in the fourth line originates from electroweak precision data. The fifth line gives limits from astrophysics and cosmology on light neutralinos. Other cosmological constraints are not included in the table. Finally, the last three lines summarize bounds from flavor and Higgs physics.

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